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SIXTH QUARTERLY REPORT

ON

"SPECTRORADIOMETRIC CALIBRATION OF THE THEMA..C MAPPER AND MULTISPECTRAL SCANNER SYSTEM"

Contract Number NAS5-27382

For the Period: 1 February 1984 - 1 May 1984

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Introduction

This is the sixth quarterly report on Contract NAS5-27382 entitled, "Spectroradiometric Calibration of the Thematic Mapper and the Multispectral Scanner System." In this report, we summarize the experiments performed during the April 1984 trip to White Sands, New Mexico. This includes the field testing of the newly built spectropolarimeter, both in the solar radiometer mode and helicopter flight test. Also included is a preprint of a paper entitled "Effective Bandwidths for Landsat-4 and Landsat-D' Multispectral Scanner and Thematic Mapper Subsystems". This is to be published in IEEE Transactions on Geoscience and Remote Sensing, May 1984.

Field Measurements

As Thursday, April 19, 1984 was the first overpass of Landsat 5 in which imagery was to be recorded over White Sands, we went to the area to take calibration measurements. Those participating were Barbara Capron, Ken Castle, Ron Holm, Ray Jackson, Carol Kastner, Jim Palmer, Amy Phillips, Richard Savage, and Phil Slater. It was cloudy and quite windy on the day of the Landsat 5 overpass and we were not able to accomplish all our objectives. Neither a complete set of solar radiometry measurements, nor reflectance measurements of the gypsum were made on April 19. Thus no data are as yet available for ground based calibration of this Thematic Mapper (TM) sensor, and in addition Langley plot data from the radiometer and Castle spectropolarimeter could not be compared. Three major goals, however, were accomplished, and are summarized below.

Castle Spectropolarimeters

This was the first opportunity to test the newly built Castle spectropolarimeters in the field. On Thursday one of the instruments was used in the solar radiometry mode. As the sun came in and out from behind the clouds the neutral density filters automatically switched into place. The instrument cycled through each of the 10 narrow band filters, recording the time of day at the start and finish of each cycle. There seemed to be a minor problem decoding one of the neutral density filter positions, which is now being corrected.

The second of the two instruments was flown, also on Thursday, onboard an Army helicopter. By measuring the radiance incident on this sensor, it is hoped that the Herman code output can be verified for an intermediate altitude of 10,000 feet above sea level. In order to mount the radiometer on the helicopter, a U-shaped bracket was built at the heliport hanger. The bracket had slits in the two side walls which the radiometer's mounting handles slid into. A slot at the bottom allowed the nose of the radiometer to view straight down. In addition the instrument could be tilted to any angle to take measurements, and also rotated 180° in place to check instrument settings while in flight.

On Thursday the helicopter departed the Holloman AFB helipad at 9:33 a.m. from a ground altitude of 4110 ft. Upon arriving at Chuck site we landed momentarily to remove the helicopter windows. Departing again at 9:55 a.m. we climbed to 10,000 ft altitude by 10:01. Just as we were in position to take readings, it was discovered that the radiometer

was frozen in a 45° position (the crew chief had tightened it down too hard just before takeoff). There was nothing that could be done but fly east of the test sight, so that the instrument appeared to be aimed in the right direction (no precise alignment technique was available). Ken Castle then cycled through the ten spectral filters on his instrument. The helicopter was repositioned, and a second data set was taken. During these two measurements the helicopter flew between 9,900 ft and 10,200 ft (a thermal prevented us from stabilizing to a more precise altitude). A third data set was taken while the helicopter was descending to the 6,000 ft level. A fourth data set was initiated, only to find that the instrument was not shifting filters. The entire flight lasted 1.5 hours. Upon landing the instrument was inspected. A loose screw was removed, after which the instrument appeared to be totally functional.

Overall the instrument performance was satisfactory. Washers were added to the mounting bracket to prevent the instrument from freezing in place during the next flight. The following describes their performance in the solar radiometer and helicopter modes in more detail.

Solar Radiometer

The instrument was operated with a five degree field of view in order to make it easier to track the sun. A tripod was used as a support but it was found to be very difficult to position the 20 lb instrument and maintain its direction of viewing. (A much sturdier and sophisticated alt-azimuth mount is currently being constructed.) The instrument also became locked, due to a software error, into a configuration where it was always looking through an ND=4 filter (the highest density filter on board). The results below show that the sun does not saturate the system in this configuration implying that the pre-design calculations were valid. A sample data run is shown below.

pol	λ(μm)	DCN	pol	λ(μm)	DCN
→	0.400	107	→	0.660	864
↑	0.400	100	↑	0.660	835
→	0.420	177	→	0.780	1339
↑	0.420	179	↑	0.780	1304
→	0.440	321	→	0.860	1415
↑	0.440	313	↑	0.860	1340
→	0.525	550	→	0.940	2039
↑	0.525	543	↑	0.940	1980
→	0.600	794	→	1.040	1694
↑	0.600	773	↑	1.040	1595

where: pol represents the polarization state transmitted for each measurement

DCN is the digital count output of the spectropolarimeter

These data are a factor of two less than the saturation level for the instrument, thus providing a reasonable margin of comfort.

Helicopter performance

The primary test proved the instrument would operate successfully when hard-mounted to a helicopter in flight. The second test was to see whether it would be able to detect the ground radiance at a height of 2000 m above ground level (AGL). The instrument was configured to have a 1 degree field of view in order to give a ground resolution of around 30 m. The following table shows the predicted values and a typical set of the measured values (the two orthogonal polarization measurements were added together to get a total value). Due to the problem with the heliocopter mount mentioned earlier, the instrument was only able to point at a 45 degree angle to the ground. (Note: the ND=0 filter was used for this test case.)

λ	E_λ	τ	ρ	L	P_{det}	R	I_{sig}	DCN	
μm	mW/cm²			mW/cm²sr	nW	A/W	na	Pred	Act
0.400	1.400	0.25	0.4	0.134	41	0.20	8.2	164	200
0.600	1.750	0.15	0.7	0.328	111	0.40	44.4	888	1000
1.040	2.640	0.05	0.6	0.477	162	0.36	58.3	1166	920

where: E is the exo-atmospheric irradiance

τ are typical optical depths

ρ are typical reflectances of gypsum

L is the ground radiance (E $\exp(-\tau \sec\theta)/\pi$

P_{det} is the power on the detector and is calculated by multiplying L by the number 3.086E-04 which is a correction factor incorporating the effects of transmission, solid angle, and aperture

R is the detector responsivity

I_{sig} is the current leaving the detector

DCN P_{red} is the expected digital counts out of the instrument

DCN A_{ct} is the actual digital counts measured

As can be seen, there is very good agreement between experiment and theory for this simple test case. Also, all the actual values are greater than 100 so that the S/N ratio is better than 100:1 for less than a 1% noise error. In general, the instrument will be operating with a 15 degree field of view when making ground observations so it should be able to see surfaces with lower reflectances. The most notable observation concerning this aspect of the instrument operation was that it was able to successfully hold the respective filter, aperture and polarizer positions while being vibrated by the helicopter platform. If it can do that, then it should operate very well in a more benign environment.

Additional data have been collected with the instrument configured with a 5 degree aperture and a full set of polarization measurements made over all the wavelengths. The instrument was pointed at right angles to the sun near sunset and the data show the sky to be 40% polarized in the blue and dropping to 20% polarized in the near IR. All the measurements appear to be consistent and so the instrument is

actually functional as a spectropolarimeter. These last measurements were taken here in Tucson.

Air photography

The first helicopter flight of the week was taken on Tuesday. It had the dual purpose of photographing the test site to be used on Thursday, and inspecting the entire area by air to determine other potential sites. The flight departed JFK heliport at 10:45 a.m., but was forced to return 10 minutes later when it was discovered that there was a scheduling conflict for the air space we had requested. After being rescheduled a second attempt was made. This time we were airborne from 11:10 a.m. to 12:06 p.m. The first area we investigated was Parker site. This is a circular area, at least 200 m in diameter, which is graded flat and used as an impact area. It was brownish in color, with different hues at different radii. Because of the nonuniformity, it is unsuitable as a test area. The pilot mentioned that other similiar, but larger, impact areas existed further north (close to the lava beds). We plan to investigate them on a later flight.

A quick trip was then made to the Northrup strip/Cherry site area. In general the sand area looked quite mottled, with well defined regions of gray intermixed with highly reflecting regions. Cherry site looked quite uniform, in comparison to many other regions. The photographer took 2 rolls of positive (slide), and two rolls of negative film, ASA 160 and 180 respectively. All pictures were shot at a focal length of 70 mm, 1/500 sec, and between F/8-11. The pictures were processed that

same day, after which it was discovered that they were overexposed and contained little useful information.

On Thursday the same films, focal length and shutter speed were used. This time they were shot at F/22-16 for the slides, and F/16-11 for the negative film. Photos were taken of Chuck site at both 10,000 ft and 6,000 ft elevation. Our sites to either side of the road looked quite uniform. The corners of our two 4X4 pixel area were well marked, allowing the photographer to zoom in on this area.

Test Site Selection and Lay Out

Our only other opportunity to do a calibration was on January 3, 1983, using an image from the TM onboard Landsat 4. There was some difficulty in identifing the location of Cherry site. Because of this it was decided to define a new test area, one which could be accurately located on the Landsat image. We therefore changed our test area from Cherry site to Chuck site. This latter area was 3.4 miles to the east of Cherry site. The new site was selected because of its uniformity and because it was located at the intersection of a nearly 100° bend in the road. As it was located along the same straight road as Cherry site, the two 4X4 pixel areas were aligned at an angle to the road from computations made for Cherry site, after inspecting the previous image. The road is known to lie 32°N of east, hence the pixel edge was adjusted such that it fell on a true east/west line. The new 4X4 pixel areas should now be closely aligned with the TM scan direction.

We would like to thank the photographer, Frank Trevino, and the pilots Jack Rees and Lt. Keyes for their co-operation and assistance. Special thanks is due Richard Savage and the management of ASL for the time they spent in helping us organize our trip and making sure our visit was as productive as possible.

IEEE Transactions on Geoscience and Remote Sensing, May 1984.

EFFECTIVE BANDWIDTHS FOR LANDSAT-4 AND LANDSAT-D′ MULTISPECTRAL SCANNER AND THEMATIC MAPPER SUBSYSTEMS

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ABSTRACT

The spectral bands of the Multispectral Scanner and Thematic Mapper subsystems of Landsat-4 and Landsat-D′ have been analyzed using a bandwidth normalization technique based on analysis of the moments of the spectral responsitivy curves. The results include the effective wavelength, the bandpass, the wavelength limits and the normalized responsivity for each spectral channel. In addition, temperature coefficients for TM PF Channel 6 have been derived. The moments normalization method employed yields sensor parameters whose derivation is independent of source characteristerics (i.e., incident solar spectral irradiance, atmospheric transmittance or ground reflectance). The errors expected using these parameters are lower that those expected using other normalization methods.

INTRODUCTION

Relative spectral responsivities for the Multispectral Scanner (MSS) and the Thematic Mapper (TM) subsystems of Landsat-4 and Landsat-D′ were obtained from Markham and Barker (1983a) and Markham and Barker (1983b), respectively. These data, provided in tabular form vs. wavelength, were analyzed using a recently described normalization technique (Palmer and Tomasko, 1980). This technique, based upon an analysis of the moments of the spectral responsivity curves, yields effective center wavelengths, bandpasses, passband wavelength limits and equivalent squareband responsivities. These parameters, when applied to the radiometric analysis of continuous sources, give results that are more accurate than analyses using conventional normalization methods. Each of the 24 detectors of the protoflight (PF, flown on Landsat-4) and flight (F, flown on Landsat-D′) MSS channels has been analyzed, and means and standard deviations have been computed for each band (6 detectors). Comparisons are shown between the previously published bandwidths and center wavelengths and those derived here. For the TM sensors, the same parameters have been obtained and comparisons are made with the conventional bandwidth determinations. In addition, a spectral responsivity plot indicating the calculated parameters are presented for a typical TM channel. Since data from Band 6 detector 4 was available at various temperatures, several temperature coefficients have been derived.

RADIOMETRIC BANDWIDTH NORMALIZATION

The output signal (assumed a voltage V) from a radiometric sensor with a spectral responsivity $R(\lambda)$ when exposed to a source (radiance from a surface, path radiance from an atmosphere, etc.) that produces a spectral irradiance $E(\lambda)$ at the sensor is

$$V = \int_0^\infty E(\lambda) \cdot R(\lambda)\, d\lambda \qquad (1)$$

In general, we wish to determine some source characteristic, and cannot do this unless both the source function and the spectral responsivity are known over the spectral interval where they are both non-zero. However, if the spectral responsivity $R(\lambda)$ can be characterized as a rectangular function which has a value Rn between wavelength limits $\lambda 1$ and $\lambda 2$ and 0 elsewhere, then we may write

$$V = Rn \int_{\lambda 1}^{\lambda 2} E(\lambda)\, d\lambda \qquad (2)$$

and the source function is thus correctly evaluated between limits $\lambda 1$ and $\lambda 2$. Radiometric bandwidth normalization is the process of assigning to a sensor with a known spectral

responsivity an equivalent squareband responsivity with well-defined wavelength limits and a constant responsivity R_n in the passband (Palmer, 1980). There have been at least 12 methods described throughout the literature, but only three will be considered here.

The most widespread bandwidth normalization method, called peak normalization, arbitrarily sets the normalized responsivity R_n equal to the peak responsivity R_p of the sensor. The bandwidth $\Delta\lambda$ is then set such that the product $R_n \cdot \Delta\lambda$ is equal to the area under the spectral responsivity curve $R(\lambda)\,d\lambda$. This method tends to give results that are lower than true radiance levels and an ambiguity exists in that there is no well-defined means of locating the limiting wavelengths or defining the effective or center wavelength.

Another popular method, called passband normalization, simply sets the wavelength limits at some arbitrarily-chosen responsivity level. A common level is the 50% point, and the resulting bandpass is called full-width at half-maximum (FWHM). Since this method is primarily used only to define a bandwidth, a value for R_n is not normally assigned. If a center wavelength is given, it is usually the center of the passband, the average of the limiting wavelengths. This method was used by Markham and Barker (1983a, 1983b).

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The normalization technique used herein was first described by Palmer and Tomasko (1980) and is called the moments method. The analysis involves determination of the first and second moments of the spectral responsivity curve. The pertinent equations are:

$$\lambda c = \int \lambda \cdot R(\lambda) d\lambda / \int R(\lambda) d\lambda$$

$$\sigma 2 = \left[\int \lambda^2 \cdot R(\lambda) d\lambda / \int R(\lambda) d\lambda \right] - \lambda_c^2$$

$$\lambda 2 = \lambda c + \sqrt{3} \cdot \sigma$$

$$\lambda 1 = \lambda c - \sqrt{3} \cdot \sigma$$

$$\Delta\lambda = \lambda 2 - \lambda 1 = 2\sqrt{3} \cdot \sigma$$

$$Rn = (\lambda 2 - \lambda 1)^{-1} \quad R(\lambda) d\lambda$$

where

λc = effective wavelength (centroid)

$\sigma 2$ = variance

Note that this method gives fixed values for the wavelength limits, the effective (center) wavelength and the normalized responsivity with no ambiguities. The derivation, given in Palmer and Tomasko (1980), shows that exact results are achieved when the source function is quadratic, and superior results are obtained in comparison with other methods for continuous sources.

Figure 1 shows a typical moments normalization result, in this case for TM flight, band 2. Note that the effective wavelength is not located at the wavelength of peak response and that the limit wavelengths $\lambda 1$ and $\lambda 2$ are not coincident with the 50% bandwidth points.

If the spectral responsivity data available is relative rather than absolute, then the desired source function cannot be determined with Equation (2). Nevertheless, the bandpasses and effective wavelengths calculated using the above method are still valid. This is indeed the case for the currently available MSS and TM data. When the absolute spectral responsivity at the wavelength of peak response is known, one need only to multiply it by the normalizing responsivity Rn to obtain the equivalent squareband response. Alternatively, the measured response to a known source can be used to determine Rn by integrating the source between wavelength limits $\lambda 1$ and $\lambda 2$ and using Equation (2).

RESULTS

This section presents the results of the moments bandwidth normalization method as applied to the Landsat-4 and Landsat-D′ MSS and TM scanners and compares them with previously derived values. For the MSS scanners, each detector was individually analyzed, and means and standard deviations were then determined for each band. Table 1 shows the summary for the MSS Protoflight instrument. The column headings are Rn for the equivalent square-band responsivity, $\lambda 1$ and $\lambda 2$ respectively for the short- and long- wavelength bandpass limits, $\Delta\lambda$ for the bandpass and λc for the effective wavelength (centroid). The columns headed TM-83955 are the center wavelengths (calculated as the arithmetic mean of the 50% band limits) and the bandpasses (FWHM) as published by Markham and Barker (1983a). Table 2 gives the summary for the MSS Flight instrument.

Comparison of the results given in Tables 1 and 2 show that the effective wavelength is the same for the two analysis methods within ±0.3% for the first three bands and about 1% for band 4. The effective passbands are somewhat different, with the moments analysis giving wider passbands than the 50% points (FWHM). The ratio of the passbands (FWHM/moments) is typically 0.95 for the first three bands and 0.8 for band 4.

TABLE 1. MOMENTS SPECTRAL ANALYSIS - MSS PROTOFLIGHT INSTRUMENT

BAND		MOMENTS ANALYSIS					TM-83955	
		Rn	$\lambda 1$	$\lambda 2$	λc	$\Delta\lambda$	λc	$\Delta\lambda$
1	MEAN	90.53	492.3	609.2	550.7	116.9	550.1	109.2
	σ	.82	.70	.97	.45	.88	.85	.69
2	MEAN	90.80	600.1	700.4	650.3	100.3	650.5	95.3
	σ	1.57	1.02	3.98	4.48	1.94	2.35	4.38
3	MEAN	84.60	695.7	812.7	754.2	117.0	756.8	111.7
	σ	1.95	1.02	1.06	1.18	0.87	0.25	1.10
4	MEAN	79.76	790.7	1062.8	926.8	272.1	915.1	215.2
	σ	2.03	1.85	9.0	7.3	5.4	6.8	13.3

TABLE 2. MOMENTS SPECTRAL ANALYSIS - MSS FLIGHT INSTRUMENT

BAND		MOMENTS ANALYSIS					TM-83955	
		Rn	$\lambda 1$	$\lambda 2$	λc	$\Delta\lambda$	λc	$\Delta\lambda$
1	MEAN	91.18	494.9	610.7	552.8	116.0	551.8	110.0
	σ	.55	1.35	1.17	.37	1.36	.85	.58
2	MEAN	91.14	600.7	698.8	649.8	98.4	649.8	93.8
	σ	.81	.75	.71	.44	.77	.42	.37
3	MEAN	85.46	698.5	814.7	756.7	115.9	759	110
	σ	.63	.61	.25	.41	.41	0	0
4	MEAN	82.60	793.7	1069.3	931.3	275.9	922.4	226.8
	σ	2.48	1.9	5.8	3.7	3.7	5.7	11.2

Table 3 shows the moments spectral analysis applied to the Protoflight TM instrument as flown on Landsat-4. The thermal band (6) is treated separately and data are available for three temperatures for one detector (4). In this case, the 50% bandwidth points were determined by linear interpolation of the relative spectral responsivity tables in the vicinity of the 50% response points. The bandwidth is the FWHM and the effective wavelength λc is midway between the 50% points. Table 4 gives the summary results for the Flight TM instrument.

Like the MSS data, there is little difference between the methods with regard to effective wavelength, but the moments method again gives wider passbands. Using data supplied by Barker (1982), it was apparent that the detectors used for band 6 display strong temperature dependences,as shown in Figure 2. The relative spectral responsivity for Band 6, detector 4 is plotted at three different temperatures (90, 95 and 105K). The temperature coefficients derived from this limited data set are shown in Table 5 with units in micrometers per Kelvin (except R).

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TABLE 3. MOMENTS SPECTRAL ANALYSIS - TM PROTOFLIGHT INSTRUMENT

BAND	Rn	MOMENTS ANALYSIS λ1	λ2	λc	Δλ	50% BW ANALYSIS λc	Δλ
1	84.75	450.3	521.8	486.1	71.5	484.9	66.1
2	83.07	526.9	615.6	571.2	88.7	569.1	80.6
3	86.73	621.3	698.4	659.8	77.1	658.7	68.7
4	93.05	771.9	906.8	839.3	134.9	840.6	129.1
5	94.65	1564	1791	1678	227	1676	216.9
7	89.17	2082	2351	2217	269	2272	250.2
6-1	75.00	10.29	11.93	11.11	1.637	11.01	1.179
6-2	74.73	10.29	11.97	11.13	1.680	11.03	1.220
6-3	75.89	10.29	11.94	11.12	1.653	11.04	1.243
6-4	77.92	10.32	11.99	11.15	1.676	11.08	1.317
6-90K	83.97	10.35	12.12	11.23	1.766	11.18	1.517
6-105K	66.69	10.22	11.79	11.01	1.566	10.87	0.915

NOTE: Band 6 data is for a temperature of 95K. Temperature data is for detector 4.

TABLE 4. MOMENTS SPECTRAL ANALYSIS - TM FLIGHT INSTRUMENT

BAND	Rn	MOMENTS ANALYSIS λ1	λ2	λc	Δλ	50% BW ANALYSIS λc	Δλ
1	85.71	451.3	521.4	486.3	70.1	485	66
2	85.13	526.2	615.0	570.6	88.9	569	82
3	84.87	622.6	698.8	660.7	76.2	659.5	67
4	89.20	771.0	905.3	838.2	134.3	840	128
5	94.74	1564	1790	1677	227	1676	217
7	89.41	2083	2351	2217	268	2223	252
6-1,3	89.27	10.45	12.46	11.45	2.014	11.43	1.963
6-2,4	93.26	10.45	12.47	11.46	2.025	11.44	1.979

Table 5. TM Band 6 Temperature Coefficients

PARAMETER	TEMPERATURE COEFF (/K)
Rn (responsivity)	-1.12
$\lambda 1$ (short wavelength)	-.0086 μ m
$\lambda 2$ (long wavelength)	-.021
$\Delta\lambda$ (bandpass)	-.013
λc (centroid)	-.014

CONCLUSIONS

An accurate radiometric bandwidth normalization method has been applied to the sensors on Landsat-4. It is recommended that the bandwidths and effective wavelengths presented herein be used in all cases where the source spectral radiance is unknown. It is further recommended that the moments method be employed to characterize future sensors.

ACKNOWLEDGMENT

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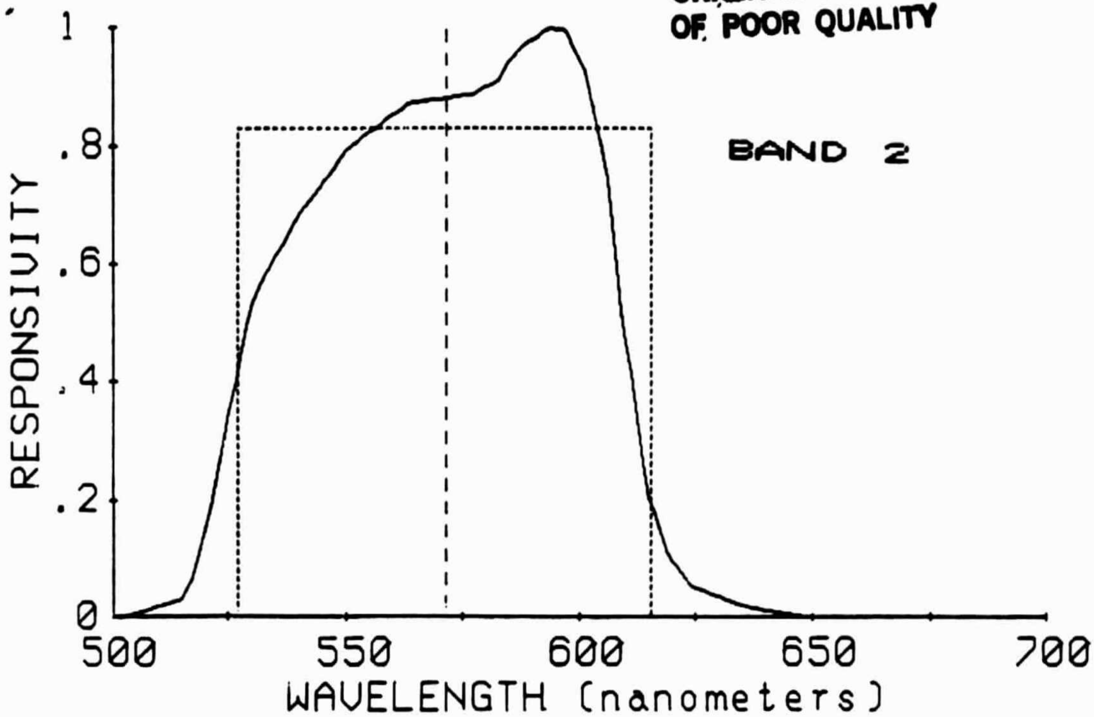
Fig. 1. Moments radiometric bandwidth normalization for a typical detector (TM PF Band 2) showing wavelength limits and Rn for equivalent squareband response and effective wavelength.

Fig. 2. TM Protoflight Band 6, Detector 4 relative spectral responsivity curves at three temperatures.


BAND 2
RESPONSIVITY
1
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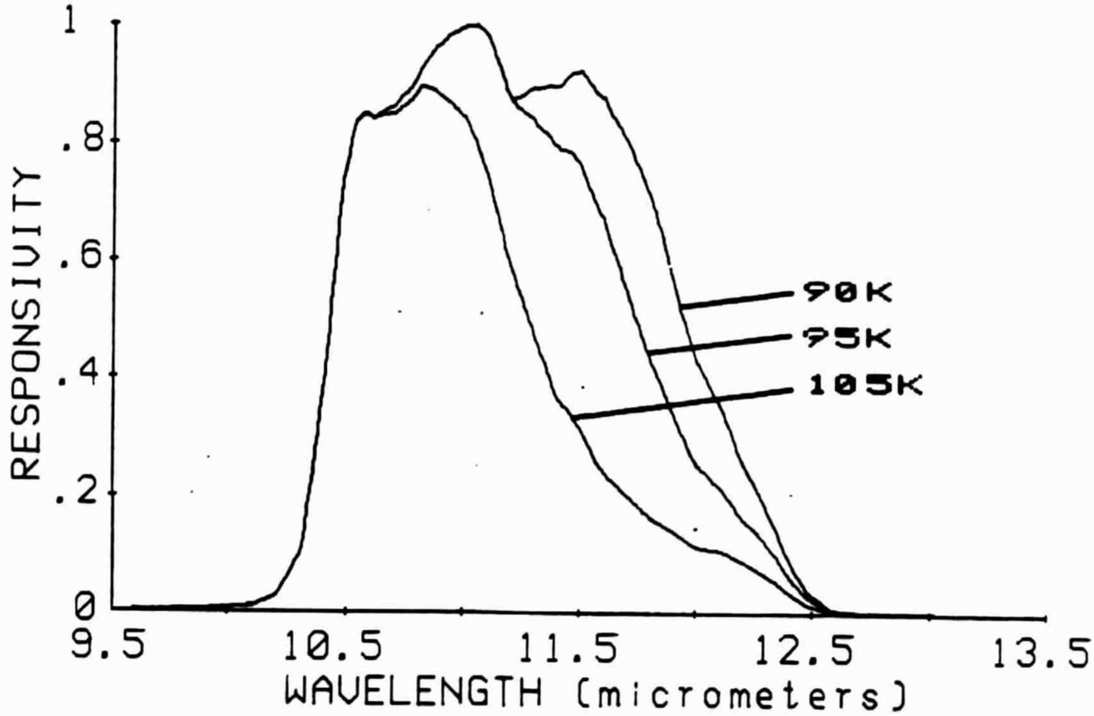
WAVELENGTH (nanometers)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90K
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